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Projection of temperature-related mortality due to cardiovascular disease in beijing under different climate change, population, and adaptation scenarios☆

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ABSTRACT

Human health faces unprecedented challenges caused by climate change. Thus, studies of the effect of temperature change on total mortality have been conducted in numerous countries. However, few of those studies focused on temperature-related mortality due to cardiovascular disease (CVD) or considered future population changes and adaptation to climate change. We present herein a projection of temperature-related mortality due to CVD under different climate change, population, and adaptation scenarios in Beijing, a megacity in China. To this end, 19 global circulation models (GCMs), 3 representative concentration pathways (RCPs), 3 socioeconomic pathways, together with generalized linear models and distributed lag non-linear models, were used to project future temperature-related CVD mortality during periods centered around the years 2050 and 2070. The number of temperature-related CVD deaths in Beijing is projected to increase by 3.5–10.2% under different RCP scenarios compared with that during the baseline period. Using the same GCM, the future daily maximum temperatures projected using the RCP2.6, RCP4.5, and RCP8.5 scenarios showed a gradually increasing trend. When population change is considered, the annual rate of increase in temperature-related CVD deaths was up to fivefold greater than that under no-population-change scenarios. The decrease in the number of cold-related deaths did not compensate for the increase in that of heat-related deaths, leading to a general increase in the number of temperature-related deaths due to CVD in Beijing. In addition, adaptation to climate change may enhance rather than ameliorate the effect of climate change, as the increase in cold-related CVD mortality greater than the decrease in heat-related CVD mortality in the adaptation scenarios will result in an increase in the total number of temperature-related CVD mortalities.

1. Introduction

Due to the concern over globally increasing temperatures, numerous studies (Zander et al., 2015, 2017; Basu, 2009; Gosling et al., 2009; Bi et al., 2011; Medina-Ramon et al., 2006; Conti et al., 2005; Lee and Kim, 2016) have focused on the public health problems, including temperature-related mortality and morbidity, and other social and economic issues (*e.g.*, labor productivity loss) caused by extreme climate events.

The Intergovernmental Panel on Climate Change (IPCC) has projected that the frequency, intensity, and duration of heat waves will increase, and unstable weather patterns are likely to occur in the coming decade (Stocker et al., 2014). Therefore, detailed projection of future temperature-related mortality is important for formulating public health policies to minimize the deleterious effects of climate change.

In the past decade, an increasing number of projections of temperature-related mortality have been performed in developed countries,

Abbreviations: GLM, generalized linear models; DLNM, distributed lag no-linear models; GCM, global circulation models; RCPs, representative concentration pathways; SSPs, socioeconomic pathways; CVD, cardiovascular disease

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but few in developing countries (Li et al., 2016; Sanchez et al., 2016). Some studies projected heat-related or cold-related deaths for a whole year or for a particular season under future climate scenarios (Petkova et al., 2014; Honda et al., 2014). Others estimated future temperature-related mortality for the total population (Guo et al., 2015; Morabito et al., 2012). However, few studies considered population change (Knowlton et al., 2007; Ballester et al., 2011; Huynen and Martens, 2015), which restricts our understanding of the emerging risks to human health caused by climate change.

In addition, previous studies (Li et al., 2016; Morabito et al., 2012) have indicated that particular populations, including the elderly, the very young, and those with existing illnesses, are more susceptible to extreme temperatures than are normal adults. Nevertheless, few data on temperature-related cause-specific mortality are available. Cardiovascular disease (CVD) (I00–I99) is now the major cause of death for both males and females in China. Thus, projection of the impact of climate change may reduce the incidence of CVD.

This study used historical data from Beijing during 2007–2009 as the baseline and combined generalized linear models (GLMs) and distributed-lag non-linear models (DLNMs) to estimate the relative risk of CVD mortality in association with the daily maximum temperature. To project future temperature-related CVD deaths, we used two global circulation models (GCMs), three representative concentration pathway (RCP) scenarios, and three socioeconomic pathways (SSPs) and developed models for two 20-year periods centered around the years 2050 and 2070. By examining a range of climate- and population-change scenarios, we aimed to assess the magnitude of future temperature-related CVD deaths in Beijing.

2. Methods

We collected historical data and downscaled future daily temperatures from 19 climate models and 3 RCPs and population projection scenarios. Then, we estimated the baseline temperature–CVD mortality relationship in Beijing, which we combined with the future daily temperature data to estimate future daily temperature-related CVD mortality under different greenhouse gas emission and population change scenarios. We also analyzed the seasonal variation in temperature-related CVD mortality.

2.1. Historical data collection

We collected historical data on daily CVD mortalities (I00-I99) in the entire population of Beijing from 2007 to 2009 from the Chinese Center for Disease Control and Prevention. Daily data on maximum temperature and relative humidity were obtained from the China Meteorological Administration. Air pollution data, including the daily concentration of PM_{10}, which was transformed based on the air pollution index (Table S1), were obtained from the Beijing Municipal Environmental Monitoring Center.

2.2. Future temperature projection

Future temperature projections were performed by exporting downscaled outputs from 19 GCMs used in the fifth IPCC reports under the RCP2.6, RCP4.5, and RCP8.5 scenarios, which are a new series of greenhouse gas emission scenarios defined by the IPCC. Among these RCP scenarios, RCP2.6 projects the lowest radiative forcing. RCP4.5 projects a stabilization scenario, with the total radiative forcing rising until 2070. RCP8.5 represents a continuously rising radiative forcing, which projects a larger increase in temperature than do RCP2.6 and RCP4.5.

We downloaded the GCM outputs from the WorldClim Database and selected climate models that are reportedly reliable for simulating climate change in China (Ying, 2012). Details of the 3 RCP scenarios and the 19 GCMs are shown in Tables S2 and S3.

2.3. Baseline temperature–mortality relationship

To assess the impact of variables other than temperature on CVD mortality, a GLM with a logarithm link and a DLNM were used to estimate the effects of several covariates on daily CVD mortality. GLM is an extension of traditional linear models and is widely used for estimating the relative rates of mortality or morbidity associated with exposure to air pollution or meteorological parameters; however, sometimes the effect of a specific exposure event is not limited to the period when it is observed but can also be delayed (Zanobetti and Schwartz, 2001). Thus, a specific statistical model should be introduced to describe the additional time dimension of the exposure–response relationship. DLNM can simultaneously represent non-linear exposure–response dependencies and delayed effects. Therefore, to describe the relationship between ambient temperature and CVD mortality more precisely, we combined DLNM with GLM to fit the exposure–response curve. The basic model is as follows:

$$\begin{aligned}\mathbf{log[E(Y_t)] = f(x_t) + NS(time, df. Time) + NS(rHumi_t, df. rHumi)} \\ \mathbf{+ NS(PM10_t, df. PM10) + DOW_t} \qquad \text{(Model1)}\end{aligned}$$

where Y_t is the observed daily CVD deaths on day t; f(x) is the DLNM model with 14 lag days; NS(time, df. Time) is the natural cubic spline of time, and df.Time is the degree of freedom per year for time, which is used to control for long-term trend and seasonality; NS(rHumi_t,df.rHumi) is the natural cubic spline of relative humidity, and df.rHumi is its degrees of freedom; and DOW_t is a categorical variable for day of the week. We also used a natural cubic spline to add the daily air pollution concentration to the model.

Similar to previous studies (Knowlton et al., 2007; Guo et al., 2012), time was modeled with 7 degrees of freedom (df) per year. PM_{10} and rHumi were each modeled using 3 degrees of freedom.

Taking the potentially non-linear and lagged relationship between ambient temperature and CVD mortality into consideration, we applied a distributed-lag nonlinear model to examine the effect of temperature on mortality. We applied a natural cubic spline with 5 degrees of freedom to daily maximum temperature. As in previous studies (Gasparrini et al., 2015; Lin et al., 2011), a natural cubic spline with 5 degrees of freedom was also used for lags of up to 14 days, which is sufficient to capture the lagging effects of temperature and would not lead to over-fitting. Previous studies (Goldberg et al., 2011; Dang et al., 2016) have summarized the relatively longer period over which cold effects take place compared with the relatively shorter period over which heat effects take place. Therefore, we selected the cumulative effects of lag0–lag3 and lag0–lag12 for hot and cold temperatures, respectively, in our main analysis.

2.4. Population

The population of Beijing during the baseline period (2007–2009) was obtained from the Beijing Municipal Bureau of Statistics. Projections of future population changes in Beijing based on SSP scenarios were obtained from Hoornwag and Pope (2014). The main assumption for population growth in the three SSP scenarios is dependent on fertility, mortality, migration, and education rates.

These assumptions describe fast, medium, and slow urbanization rates for SSP1, SSP2, and SSP3, respectively (Lutz et al., 2014). Details of the three SSP scenarios are shown in Table S4. In the three SSP scenarios, countries are categorized based on their current fertility rate, high ($>$ 2.9 children per woman) or low ($\leq$ 2.9 children per woman), for low- and medium-income nations. The third category consists of OECD and high-income nations; these follow the World Bank definition. The education rates are based on projections in IIASA/VID, in which a high rate represents global expansion of school systems at the fastest possible rate, which is based on recent examples such as Singapore and South Korea. A medium rate represents a scenario in which countries

follow a path similar to those of other countries with a similar level of educational development, and a low rate indicates that educational levels are maintained at current levels. In addition, we assumed constant baseline mortality rates in our projection.

2.5. Projecting future temperature-related deaths due to CVD

Future temperature-related CVD deaths in Beijing were projected by combining the projected future daily maximum temperature and the baseline temperature–CVD mortality relationship. To obtain the future daily maximum temperature, the monthly average differences between the baseline climate and the future climate from models were added to the baseline daily maximum temperatures in the same month.

Next, a time series of future daily maximum temperatures was used to compute future temperature-related CVD deaths. For temperatures higher than the maximum daily temperature, we estimated the corresponding mortality based on the nonlinear relationship from the baseline time period (2007–2009). The optimum temperature (OT) was defined as the temperature at which the number of deaths is smallest. For any day with a maximum temperature higher than the OT, the change in mortality due to the effect of heat was calculated relative to that at the OT. For any day with a maximum temperature lower than the OT, the change in mortality due to the effect of cold was calculated relative to that at the OT. The numbers of heat- and cold-related deaths were summed to calculate the total number of temperature-related deaths.

We used the method of Gasparrini and Leone (2014) to calculate daily temperature-related mortality.

2.6. Adaptation

Adaptation is another concern. The percentile OT value among all daily maximum temperatures is relatively stable in one location (Honda et al., 2014). Therefore, it is possible to estimate the future OT by calculating the percentile of OT in the baseline climate. We assumed 0% adaptation when the OT of the baseline climate was used and 100% adaptation when the OT of the future climate was used. The midpoint of the OTs of the above two types was defined as 50% adaptation. The average number of annual heat-related deaths that took into consideration adaptation were computed using the future daily maximum temperature and adjusted temperature–mortality relationship based on the adjusted OT.

2.7. Sensitivity analysis

Sensitivity analyses were performed by varying the maximum lag to 21 days and the degrees of freedom for lag time from 6 to 8 and assessing the effects on the modeling results. The sensitivity analysis results are shown in Figs. S1 and S2. Compared with the overall effects of daily maximum temperature over 14 days on CVD-related mortality, the effect on the sensitivity results was negligible.

3. Results

Table S5 shows a summary of the daily weather conditions, air pollutant concentrations, and mortality rates in Beijing from 2007 to 2009. The average daily maximum temperature and relative humidity were 18.9 °C and 52%, respectively. The average daily number of deaths due to CVD was 87.

Table S6 shows a summary of the projected daily maximum temperature (°C) in the 2050s and 2070s using 19 GCMs and the RCP2.6, RCP4.5, and RCP8.5 scenarios. Applying the same GCM, the future daily maximum temperatures projected under the RCP2.6. RCP4.5, and RCP8.5 scenarios show a gradually increasing trend. The future daily maximum temperature in the 2070s is higher than that in the 2050s using the same GCM and emissions scenario. These increases support

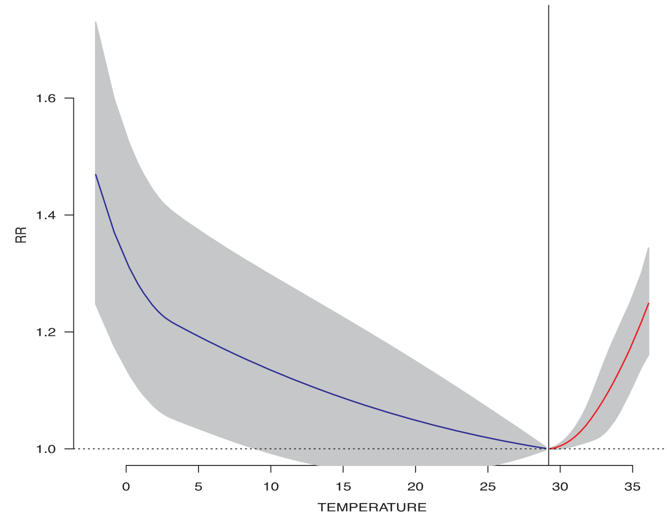

Fig. 1. Estimated overall effect of the daily maximum temperature over 14 days on CVD mortality.

the projection in the fifth IPCC report, which predicted increases in global mean surface temperature during 2046–2060 relative to 1986–2005 in the ranges of 0.4 °C to 1.6 °C (RCP2.6), 0.9 °C to 2.0 °C (RCP4.5), and 1.4 °C to 2.6 °C (RCP8.5).

Fig. 1 shows the estimated effect of maximum temperature over 14 days on deaths due to CVD. The curve is U-shaped at lags of 0–14 days, with an OT of 29.2 °C. Both hot and cold effects were apparent, which is in accordance with the climate of Beijing. When the temperature was lower than the OT, the risk of mortality due to CVD decreased as temperature increased; when the temperature was higher than the OT, the risk of mortality increased as temperature increased. The relationship between temperature and CVD mortality with 14 lag days is shown in Fig. S3.

We next applied the temperature–mortality function in Fig. 1 to daily temperatures extracted from 19 GCM models to estimate the effect on temperature-related deaths. Table 1 shows the average increase in temperature-related mortality for the three RCP scenarios during the 2050s and 2070s compared with that during the baseline period.

Fig. 2 shows the distribution of average annual temperature-related CVD deaths during the baseline period, 2050s, and 2070s for 19 climate models and the RCP2.6, RCP4.5, and RCP8.5 scenarios, without considering population change. Applying the same climate model, the annual number of temperature-related CVD deaths projected using the RCP2.6, RCP4.5, and RCP8.5 scenarios exhibited a gradually increasing trend before the 2050s. For the second half of the 21st century, the number of temperature-related CVD deaths is projected to increase under the RCP4.5 and RCP8.5 scenarios. In contrast, the number of temperature-related CVD deaths is projected to stay the same or decrease slightly under the RCP2.6 scenario, possibly due to lower emission of greenhouse gases in this scenario. For instance, with the BCC-CSM1.1 model under the RCP8.5 scenario, the average annual number of temperature-related CVD deaths was 3555 and 3697 in the 2050s and 2070s, which are 13.5% and 18.0% increases, respectively, compared with the baseline period (3133 deaths).

Fig. 3 shows the seasonal changes in the number of temperature-related CVD deaths under future climate scenarios. Beijing, which is located at the northern tip of the North China Plain, typically experiences a hot, humid summer and a cold, windy, dry winter. The average number of temperature-related CVD deaths increases by > 80% in summer and decreases slightly in autumn and winter. Furthermore, the pattern of seasonal variation differed among the three scenarios. In summary, the RCP8.5 scenario had a greater impact on seasonal variation than did the RCP2.6 and RCP4.5 scenarios.

Projections of the annual number of cold- and heat-related CVD

Table 1
Variation in temperature-related mortality (°C) during the 2050s and 2070s compared with the baseline period under the RCP2.6, RCP4.5, and RCP8.5 scenarios.

RCP scenario	GCM	Annual net		Cold-related		Heat-related	
		50 s	70 s	50 s	70 s	50 s	70 s
RCP2.6	AC						
RCP2.6	BC	334	315	− 113	− 185	448	500
RCP2.6	CC	83	115	− 188	− 158	271	273
RCP2.6	CE						
RCP2.6	CN	132	194	− 75	− 67	207	261
RCP2.6	GF	62	81	− 468	− 376	530	457
RCP2.6	GD	446	276	275	199	171	77
RCP2.6	GS	− 6	47	− 177	− 124	172	171
RCP2.6	HD	77	− 41	− 267	− 382	344	341
RCP2.6	HG						
RCP2.6	HE	40	1	− 374	− 333	414	334
RCP2.6	IN						
RCP2.6	IP	− 45	− 80	− 392	− 344	347	265
RCP2.6	MI	101	275	− 388	− 343	488	618
RCP2.6	MR	268	103	− 461	− 413	729	516
RCP2.6	MC	9	124	− 186	− 225	195	349
RCP2.6	MP	200	162	− 199	− 117	398	279
RCP2.6	MG	243	191	108	103	135	88
RCP2.6	NO	123	− 79	− 163	− 382	286	302
RCP2.6 Average		137.8	112.27	− 204.53	− 209.8	342.33	322.07
RCP4.5	AC	176	428	− 362	− 569	538	997
RCP4.5	BC	159	275	− 259	− 311	418	586
RCP4.5	CC	50	144	− 224	− 307	273	451
RCP4.5	CE	843	858	− 402	− 693	1245	1552
RCP4.5	CN	49	55	− 135	− 248	184	303
RCP4.5	GF	198	284	− 419	− 438	617	722
RCP4.5	GD	239	62	44	− 161	195	223
RCP4.5	GS	− 48	− 35	− 295	− 354	247	319
RCP4.5	HD	− 39	− 57	− 253	− 566	214	509
RCP4.5	HG	29	− 57	− 371	− 433	400	376
RCP4.5	HE	− 53	155	− 416	− 522	363	678
RCP4.5	IN	235	337	210	306	25	30
RCP4.5	IP	34	− 16	− 392	− 551	427	536
RCP4.5	MI	141	357	− 335	− 541	476	898
RCP4.5	MR	52	296	− 408	− 692	460	988
RCP4.5	MC	− 13	− 27	− 264	− 358	251	331
RCP4.5	MP	185	238	− 332	− 336	517	574
RCP4.5	MG	173	165	36	− 58	137	223
RCP4.5	NO	154	65	− 239	− 441	393	506
RCP4.5 Average		134.95	185.63	− 253.47	− 382.79	388.42	568.53
RCP8.5	AC	372	359	− 419	− 744	791	1103
RCP8.5	BC	421	474	− 367	− 592	789	1065
RCP8.5	CC	172	341	− 319	− 580	490	922
RCP8.5	CE						
RCP8.5	CN	115	39	− 265	− 503	380	542
RCP8.5	GF	240	627	− 625	− 946	865	1574
RCP8.5	GD						
RCP8.5	GS	− 83	− 55	− 353	− 589	270	534
RCP8.5	HD	164	258	− 487	− 804	651	1062
RCP8.5	HG	26	473	− 476	− 809	501	1282
RCP8.5	HE	78	393	− 614	− 898	692	1290
RCP8.5	IN	402	52	194	− 189	208	240
RCP8.5	IP	9	335	− 627	− 848	636	1183
RCP8.5	MI	299	486	− 670	− 890	969	1376
RCP8.5	MR	115	639	− 629	− 1050	744	1690
RCP8.5	MC	28	145	− 360	− 598	388	743
RCP8.5	MP	289	423	− 370	− 652	659	1075
RCP8.5	MG	274	139	62	− 457	211	596
RCP8.5	NO	138	299	− 343	− 653	481	953
RCP8.5 Average		179.94	319.24	− 392.24	− 694.24	572.06	1013.53

deaths, taking into account population change and adaptation, are shown in Fig. 5. Overall, cold weather contributes most to temperature-related CVD deaths. In comparison with no population change, in the 2050s, Beijing is expected to experience a > 60% increase in temperature-related CVD deaths compared with the baseline period under the RCP8.5 and SSP1 scenario, compared with a 6% increase under the RCP8.5 and no-population-change scenario. Thus, temperature risks could be underestimated if population change is not considered.

Figs. 4 and 5 show temperature-related CVD mortality under different adaptation scenarios. The dotted lines represented the baseline mortalities in heat and cold days, which are 250.207 and 2819.89 respectively. The projected number of heat-related deaths was reduced by substantial adaptation to climate change, but it remained higher than that of the baseline period. However, the number of cold-related deaths may be increased by adaptation to higher temperatures. For instance, the number of cold-related deaths during the 2050s was increased by 548 under the RCP8.5% and 100% adaptation scenario compared with that under the RCP8.5% and 0% scenario. Moreover, the number of

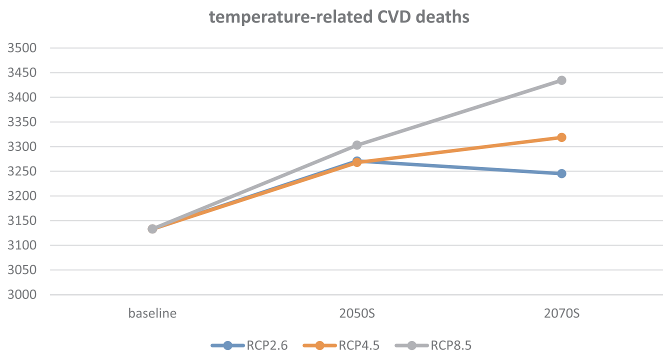

Fig. 2. Distribution of annual temperature-related CVD mortalities during the baseline period, 2050s, and 2070s under three RCP scenarios, with no population change.

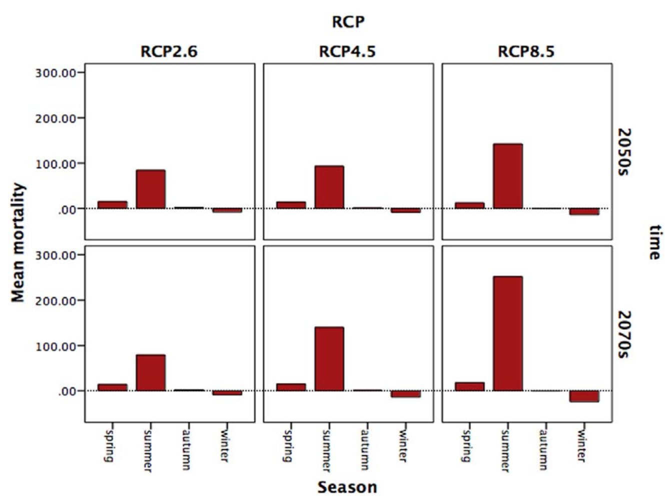

Fig. 3. Projected percentage change in seasonal temperature-related CVD mortalities under climate scenarios in the 2050s and 2070s, compared with the baseline period.

heat-related deaths during the 2050s was decreased by 496 under the RCP8.5% and 100% adaptation scenario compared with that under the RCP8.5% and 0% scenario. Thus, the overall number of temperature-related CVD deaths would increase by 52 under the above scenarios. Because the decrease in cold-related mortality caused by adaptation cannot compensate for the increase in heat-related mortality, the overall temperature-related mortality increases under scenarios involving adaptation to climate change.

The variation in the number of cold- and heat-related CVD deaths shows opposing trends according to emission scenario. Although the number of heat-related CVD deaths shows an increasing trend under RCP scenarios with rising radiative forcing, the number of cold-related CVD deaths shows a decreasing trend. These opposing trends can be used to explain the variance among seasons (Fig. 3).

4. Discussion

This study projected future temperature-related CVD deaths under two GCMs, three RCP scenarios, and three SSP scenarios for two future periods centered around the years 2050 and 2070. To our knowledge, this is the first study in Asia to explore the effect of climate change on disease-specific mortality rather than the total number of temperature-related deaths. Furthermore, three SSP scenarios were evaluated in this work; few previous studies on this topic have considered population change.

The relationship between CVD mortality and ambient temperature has been investigated previously (Zhang et al., 2014; Moran et al., 2010; Braga et al., 2002; Yang et al., 2012). Because this relationship varies geographically, it must be investigated in individual countries to facilitate formulation of local public health policies. Compared with the previous temperature–CVD mortality relationship in Beijing (Zhang et al., 2014; Yang et al., 2012), the OT was the 75.5th percentile of temperature, which is in accordance with the range of OT (70–99th percentiles of temperature) reported in a previous study (Yang et al., 2012).

Our data provide evidence of an increase in the temperature-related CVD mortality rate compared with that of the baseline period in Beijing. The increasing trend of temperature-related CVD deaths in different RCP scenarios is generally consistent with previous reports (Li et al., 2013; Guo et al., 2016), while the absolute numbers of heat-related deaths differs, because China is the most populous country.

During the 2050s, the maximum increase in temperature-related CVD mortality in Beijing was 63.7%, which is lower than that (73.8%) reported in a previous study (Li et al., 2015). Thus, the projected rate of increase is lower for temperature-related mortality than for heat-related mortality in studies of the same area. This difference may be because of the different baseline periods used or methods of calculating future temperature-related mortality. This lower increase could also be due to the reduction in cold-related mortality, which could in part balance the projected increase in heat-related mortality. Compared to the five GCMs and generalized semi-parametric Poisson regression model used to model the temperature-mortality relationship in the previous study, the 19 GCMs and DLNM model used in our study can represent non-linear exposure-response dependencies and delayed effects simultaneously and thus yield more reliable results.

To clarify the changes in temperature-related CVD death over an entire year, we also examined seasonal changes in temperature-related CVD death. The temperature-related CVD mortality rate was significantly higher in summer and slightly lower in autumn and winter under different RCP scenarios. Previous studies (Li et al., 2013; Guo et al., 2016) of monthly changes in temperature-related CVD mortality also reported increases during months with high temperatures, and *vice versa*.

Few previous studies took population changes into consideration. These either assumed a constant population size or considered a simple rate of population increase instead of using social economic scenarios. This study hypothesized future population change using various SSP scenarios. According to Table S4, the SSP1, SSP2, and SSP3 scenarios represent respectively sustainable, dynamics as usual and Fragmented future develop path. Our findings projected the number of temperature-related CVD deaths in Beijing depending on the degree of future urbanization. Such data may facilitate the development of measures that reduce the deleterious effects of climate change in Beijing.

The effect of climate change would likely be ameliorated by substantial adaptation. However, there is no consensus on how to estimate this effect. In this study, we changed the OT according to the percentile of OT in the range of daily temperature to explore the effect of adaptation. The increase in heat-related CVD mortality was greater than the decrease in cold-related mortality caused by adaptation. Thus, adaptation to climate change may enhance rather than ameliorate its effects.

Compared with the no-adaptation scenario, heat-related mortality was decreased by 20–50% depending on the degree of adaptation, which is in partial agreement with the reported effect of adaptation in the U.S. (Hayhoe et al., 2004). However, because adaptation involves not only physical adjustment to the ambient environment but also changes in land-use pattern and living habits, the willingness of different population subgroups in different regions to adapt is unclear.

The mechanism underlying the effect of temperature on CVD mortality is complex and involves changes in vascular tone, autonomic nervous system response, arrhythmia, and oxidative stress. Exposure to high temperatures may cause dehydration, salt depletion, and increased surface blood circulation, leading to thermoregulation failure, which is

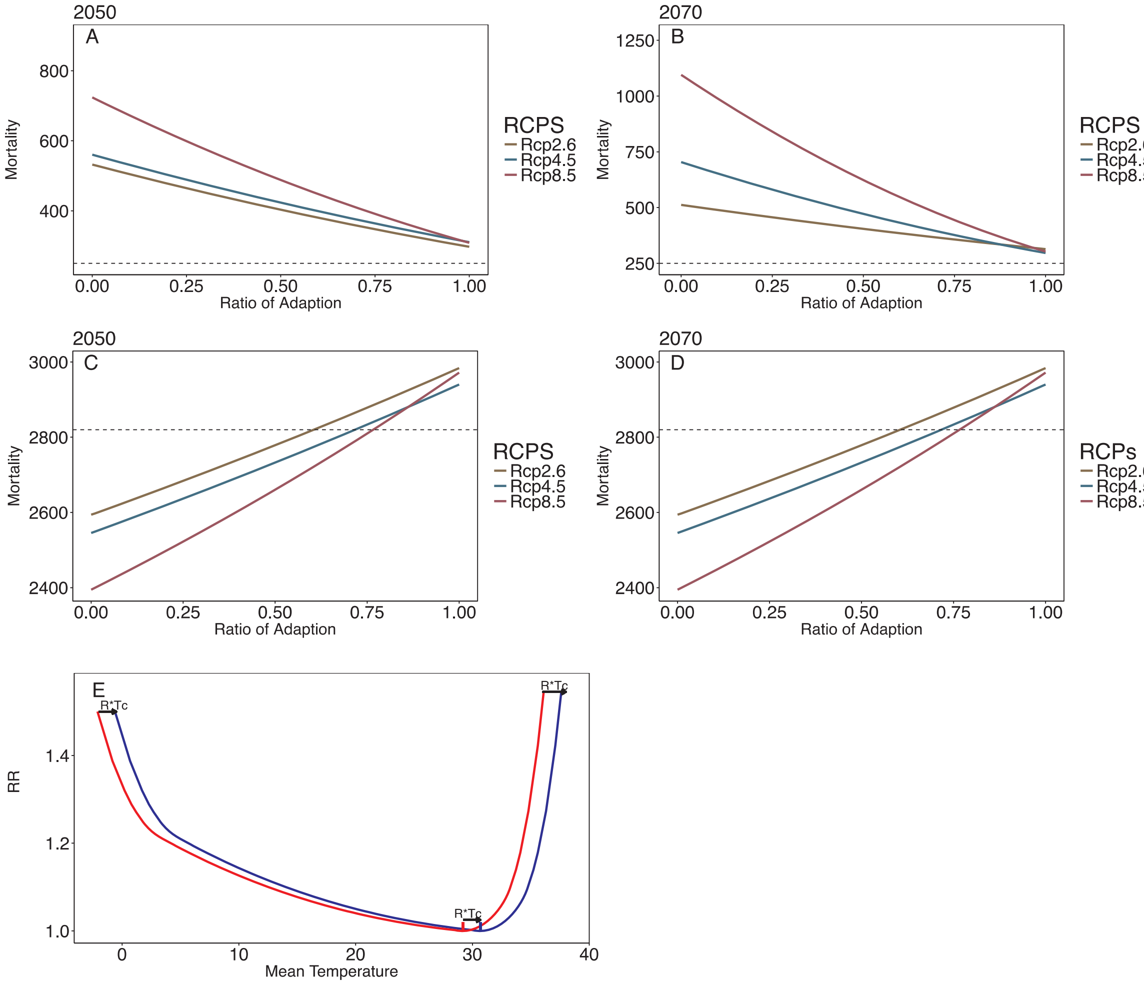

Fig. 4. Effect of adaptation to climate change on heat-related CVD mortality (a, b) and cold-related CVD mortality (c, d) during the 2050s and 2070s. (e) Variation of OT when adaptation is considered.

a risk factor for CVD (Zhang et al., 2014). Exposure to low temperatures may be associated with an increase in blood pressure, blood cholesterol, heart rate, and other factors related to CVD (Zhang et al., 2014). Therefore, projections of the effect of climate change must consider both cold and heat-related CVD mortality.

This study had several limitations. First, because the response to low and high temperatures is influenced by age, sex, and economic status, the projected number of temperature-related CVD deaths may differ among subgroups. Because of the aging of the population, the proportion of younger age groups will decrease, and vice versa, which may result in underestimation of future temperature-related CVD mortality.

Moreover, the relationship between temperature and CVD mortality was assessed using data for only 2007–2009, which reduces the reliability of the results. However, in the section of sensitivity analysis, we found that the temperature-mortality curve remains relatively stable although only three-year data were included.

In addition, the inclusion of adaptation in the models can result in greater uncertainties than those associated with climate and emissions. The range of impact including and excluding adaptation for the 'relative threshold shift' method used in our study is 94%. Among the six main methods applied in Gosling's research, the 'Relative threshold shift' method is the only method supported by empirical evidence (Gosling et al., 2017). Also, on the assumption that the future OT has the same percentile value as the present-day OT can be justified by Åström research which states that the relative OT remained relatively stable after the 1970s (Åström et al., 2015). Nevertheless, the limitations of this methods cannot be ignored. The 'Relative threshold shift' method is only supported by a single research from Japan (Honda et al., 2014) and the statistical range of this methods is larger than only methods that compared in Gosling's research. In summary, there is no consensus on which adaptation methods is the best to consider the adaptation effect on temperature-related mortality. In the future, more comprehensive methods are needed in order to provide a more holistic picture of potential climate change effects.

5. Conclusion

The number of temperature-related CVD deaths in Beijing is projected to increase compared with that during the baseline period. The decrease in the number of cold-related CVD deaths does not compensate for the increase in that of heat-related deaths, leading to an increase in the total number of temperature-related CVD deaths in Beijing. Using the same GCM, the future daily maximum temperature projected under the RCP2.6, RCP4.5, and RCP8.5 scenarios shows a gradually increasing trend. When population change is considered, the annual number of temperature-related CVD deaths is considerably greater than that under the no-population-change scenario. Moreover, adaptation to climate change may enhance rather than ameliorate its effects. Because few studies have projected the number of heat-related deaths in China, our work may be useful for formulating public health policy.

Fig. 5. Projected annual numbers of cold- and heat-related CVD deaths under the RCP2.6, RCP4.5, and RCP8.5 scenarios considering changes in population and adaptation to climate change.

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Competing interests

there is no conflict of interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2017.12.027

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